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Research Article

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Using Theory of Constraints to Control Manufacturing Systems: A Conceptual Model

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Abstract

Since the Goldratt and Cox's (1984) seminal study, Theory of Constrains has evolved from a simple production scheduling software into a management philosophy, with practices and principles spanning a multitude of operation management disciplines. A variety of studies has investigated how production control is carried out in a Theory of Constrains environment, but most of research available lacks in providing an overall vision of this issue. In order to contribute to this gap, using theoretical investigation and the empirical study of five case studies, this article compares the characteristics of TOC with those typical of three shop floor control systems, i.e. MRP, JIT and Daily Rate. As result, the research identifies an interpretative framework based on the distinguishing characteristics of Theory of Constrains. The framework supports the analysis of the nature and scope of these four systems by highlighting the main differences between them.

Keywords: Operations management; Theory of constraints; Drum-buffer-rope; MRP; JIT; Daily rate

Introduction

The story of Theory of Constraints (TOC) is indissolubly tied to that of Optimized Production Technology (OPT), a production planning and control system which was initially formalized in 1980s by the Goldratt' writings. The OPT system was introduced as a proprietary software product originally sold from Creative Output, Inc. to identify and manage the bottlenecks in the manufacturing process and introduce a method of creating a finite production schedule for the bottleneck operations [1].

Throughout the 1980s, OPT underwent significant modification to became an entire production control philosophy, called Theory of Constraints [2-4]. The TOC philosophy focuses on constraints - defined as anything that limits a system from achieving higher performance versus its goal – and it capitalizes their role improving the production planning and control system's performance.

The procedure that provides on going improvement consists of the following five steps: 1. Identify the constraints; 2. Decide how to exploit the constraints; 3. Subordinate everything else to the action taken in 2; 4. Elevate the constraint; 5. if in step 4 the constraint is eliminated, do not let inertia become a new constraint. Moreover, TOC uses several specific techniques to aid in accomplishing the five focusing steps. Among these, the drum-buffer-rope mechanism is surely one of the best known [5,6].

Even if the two terms, TOC and OPT, are used somewhat interchangeable in the literature, they refer to two different components, namely, a philosophy which underpins the working system and a software package that produces manufacturing schedules through the application of this philosophy to the manufacturing system. Therefore, given the overlapping between the two approaches, in reviewing literature and in analysing case study we consider both OPT and TOC approaches.

The paper is organized as follows:

Section 2 provides a literature review of TOC/OPT characteristics by comparing them with MRP and JIT production management approaches. The literature review highlights that the most significant differences are pertinent to the third level of the manufacturing planning and control system, the so-called production executive control or shop floor control sub-system. Section 3 identifies a suitable research framework for driving the empirical investigation. The Melnyk et al.'s (1985) model is chosen as it carefully identifies and describes the activities managed by a Shop Floor Control (SFC) sub-system [7]. The next section illustrates the research methodology used to investigate empirically the identified activities. Section 5 supplies a comprehensive description on how a group of investigated firms manage shop floor control activities. Section 6 illustrates the results of the cross-case analysis and proposes an interpretative framework for discussing the distinguishing characteristics of TOC in production control. The framework is articulated on eleven elements characterising the TOC/OPT approach and differentiating it from three other shop floor control systems, i.e. MRP, JIT and Daily Rate.

Toc vs. Mrp and Jit: A Literature Review

Since 1980s, there had been several implementations of the OPT software and TOC systems and many studies were being published in the literature. A number of these works focused on the characteristics of the OPT/TOC in comparison with other production control systems such as MRP and JIT [8,9].

With respect to the OPT-MRP comparison, some papers highlighted the shortcomings of MRP and the superiority of OPT [10]. Goldratt [11] pointed out that the product-process structure of the OPT overcomes two key limitations of the MRP system, as it does not require the separation between product structure (bill of materials) and process structure (product routing). Some authors reported that a

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company might need both tools: MRP for net requirements and OPT for realistic shop schedules [10,12]. In this perspective, OPT is viewed as a powerful shop floor control technique which may be considered as an enhancement to MRP. However, using a simulation, Duclos and Spences [13] pointed out that the scheduling procedure under theory of constrains, called drum-buffer-rope, produce significant better result than the MRP method used at the factory and they demonstrated that trying to combine the perceived strengths of two different production techniques may not yield satisfactory results.

As regards the relationship between TOC/OPT and just-in-time (JIT), Schonberger [14] concluded that JIT is similar to OPT in many aspects because kanban is an effective approach to managing the constraints. Lambrecht and Decaluwe [15] developed a simulation study to compare OPT with JIT. The results of their simulation indicated that both JIT and OPT offered useful insights as well as improvements over MRP. In addition, Atwater and Chakravorty [16] used a simulation analysis, which showed TOC system performed best when station variability is high, but when station variability is low, JIT achieve best performances. Vollum and O'Malley [17] discussed ways in which JIT would improve by using OPT. They concluded that there were no major problems with combining JIT and OPT methods where OPT scheduled the bottlenecks and JIT scheduled non-bottlenecks. Hansen [18] also explored JIT and TOC compatibility and he concludes "JIT/TOC can form a natural evolutionary marriage that will enable us to not only compete in a world class manufacturing environment, but to literally leap from the competition". Wheatly [19] describes OPT software as "OPT is simply a JIT technique that is applicable to non-repetitive industrial environments where kanban flounders".

Many studies in the literature have tried to make a simultaneous comparison of OPT, MRP and JIT [20,21]. Most of these works underlines that manufacturing systems employing TOC technique exceed the performance of those using MRP and Just in Time, as TOC systems increase output while decreasing both inventory and cycle time [22,23].

Everdell [24] reviewed the three production planning and control systems (JIT, MRP and OPT) and he underlined that JIT proceeds one step further than OPT and does synchronize operations and eliminates a lot of 'Murphys' that OPT recognizes as restraints. However, OPT, like JIT does not address all the planning support activities of MRP-II". Aggarwall [8] found that the three production systems could all operate effectively since all three incorporate the five production planning and control functions within them. Each system has its advantages and disadvantages.

Plenert and Best [25] wrote that both JIT and OPT are more productive than MRP, and the OPT system is more complete than the JIT system. Sohal and Howard [26] support the conclusions reached by Plenert and Best. Grunwald et al. [27] highlighted different evidences. Based on a framework designed to compare different production planning and control systems, they conjectured that OPT operates best under conditions of high complexity and low uncertainty, MRP operates best under conditions of high complexity and high uncertain.

Ramsay et al. [22] carried out a simulation study and they conclude that the OPT approach appears to be most useful of the three.

Production Control in Manufacturing Systems: a Research Framework

As pointed out by in the above literature review, the production systems operating in accordance with a TOC/OPT approach show specific operational characteristics in all three levels, which traditionally comprising a Manufacturing Planning and Control System (Figure 1a) [28].

A deeper analysis highlights that the most significant changes are on the third level of a MPCS, which, according to Vollmann et al. [28], focused on the *executive control* of the production plans. Consequently, in order to understand how the TOC/OPT systems operate and their differences with other production systems, our study

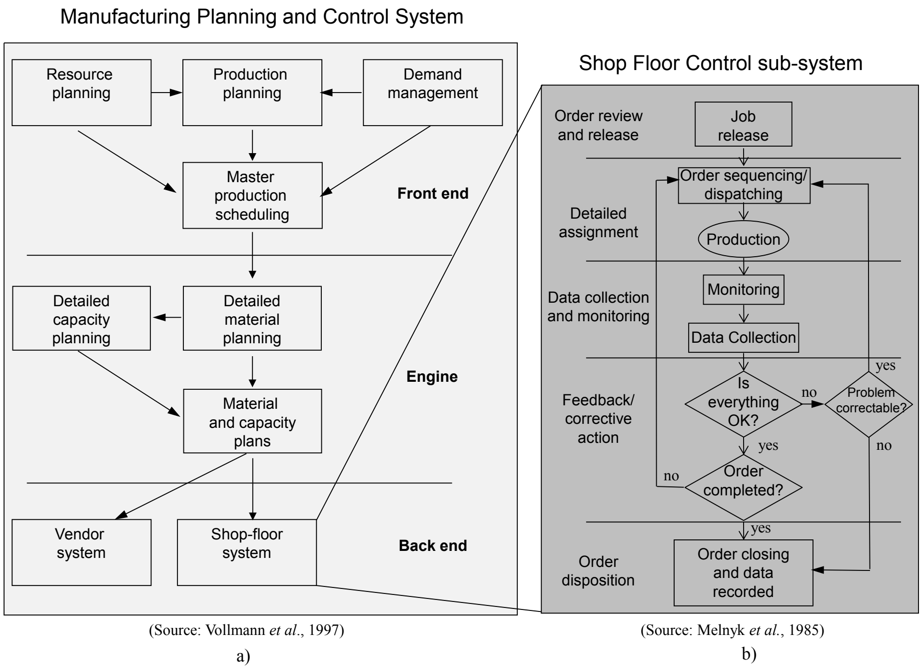

Figure 1: The research framework for shop studying floor control in TOC environment.

investigates the activities which traditionally concern the executive control of production such as material availability check and material withdrawals, release of production order, production order scheduling and order settlement. All these activities directly affect the flow of materials through the factory and constitute the so-called Shop Floor Control sub-system.

For carrying out the empirical study, the Melnyk et al.'s [7] model was chosen as a reference framework (Figure 1b). As shown in Figure 1b, this model supplies a whole representation of the activities managed by the Shop Floor Control (SFC) sub-system. Its five groups of activities-i.e. *Order review/release; Detailed assignment; Data collection/monitoring; Feedback/corrective action; Order disposition*– are briefly described in the following (Figure 1).

Order review/release includes those activities, which must take place before an order can be released to the shop floor. These activities are necessary firstly, to control the flow of information and orders passing from the planning system to the execution system and secondly, to ensure that the orders released have a reasonable chance of being completed by the expected time and the quantity.

The *detailed assignment* refers to the activities supporting the precise assignment of resources. Traditionally, this defines for each work centre the sequence of operations to be carried out according to determined priorities.

The third group of activities, i.e. *data collection and monitoring*, is essential for the accurate regulation of production, as it links the planning system with the execution system. The information pertaining to the actual progress of an order as it moves through the shop includes current location of the shop order; current state of completion; actual resources used at current and preceding operations; any unplanned delays encountered.

The fourth group of activities is named *feedback/corrective action*. Corrective action is required by management any time the actual progress of a shop order exceeds some predefined margin of difference from its planned progress. In the presence of not conform orders the production plans corrective actions are taken in the very short term.

The final set of activities included in Shop Floor Control is *order disposition*. The order has been completed (or is no longer usable because of scraps) and it goes out of the SFC sub-system. Order status is modified from open to close. In this last stage, information about the closed order is recorded. This information is crucial for cost accounting, cost planning and review of standard data used in planning of medium and long term capacities.

Research Methodology

The research process was based on in-depth literature review and empirical investigations. In analysing literature, we adopted an approach that combined elements of systematic literature review (Rousseau et al., 2008; Denyer and Tranfield, 2008) with the authors' previous knowledge of the OPT field developed over the past 15 years [29,30].

As describe in the previous section, our empirical analysis focused on SFC sub-system. Following the writings of Voss et al. [31] and Huberman and Miles [32], in the empirical investigation we analysed five groups of activities proposed by Melnyk et al.'s [7] framework (Figure 1b).

In order to carry out the empirical study, we selected five manufacturing Italian SMEs (i.e. independent firms employing less the 250 people and with a turnover not exceeding 50M euros or with a balance sheet total not exceeding 43M euros), which have successfully adopted the TOC philosophy in recent years. The unit of analysis was the single plant. The data were collected while visiting the companies and interviewing persons that operated in the production planning and control office. For each company, we conducted semi-structured interviews, we recorded data electronically and we took notes. During initial interviews, we asked general questions about the history, clients, structure, human resource education and practices, and work process. Subsequent interviews focused on the five groups of activities previously described (Figure 1).

A rich amount of primary data was gathered and, throughout the research process, we deliberately sought confirmation leads to more reliable results. We looked for multiple sources of evidence for each of the investigated elements using the triangulation technique [33]. In addition to production planning and control managers, we interview other persons belonging to different departments. The use of multiple data evidence and the use of archival data helped authors crosscheck pertinent information and verify the reliability of the data obtained. Moreover, to ensure internal validity, the authors recorded evidence of other factors that could be used as alternative explanations to the observed patterns [34,35].

After the case visit, the tape recording were transcribed and, whenever possible, additional data were added to it using further evidence (like observation, documents and other material collected in the field), idea and insights that arose during the visits. Subsequent, all the information were brought together using the categorical aggregation and interpretation technique, which brings instances together until something can be said about them as a group [36,37]. As it will be describe in section 6, eleven activities are selected to support the comparison between Dispatching, Kanban, Daily Rate and TOC/OPT.

Empirical Investigation

The case studies are presented as follows. Firstly, a brief description of the production process is given; then, a discussion of the production planning environment is developed. To ensure anonymity, the letters A, B, C, D and E identified the firms.

Company A

Theory of Constraints was implemented within the fabrication of a metal component for an automotive engine bearing. In this setting, three different types of this component are produced over a partially dedicated process. At the time of the implementation, aggregate weekly demand for the three parts was approximately 180,000 units, with fairly level forecasts for several months into the future.

First, the part is machined on the screw machine centres from bar stock, and then it is hardened in a heat treat non-dedicated batch furnace. After a hardness check by a metallurgical lab, each part is further machined through several grinding operations. Afterward, the outside diameter is machined to specification through two grinding operations performed on the same machine. The next grinding operation is performed on one of eighth bore grind machines. After length inspection, outside diameter, and bore size, the part is sent to a final crown grind operation. Two final inspect operations check for visual defects and hardness.

The bore grind operation is established as the control point. The identification of this re-source as the bottleneck is simple since it is the only department to run six (and often seven) days per week.

The master schedule showing daily planned production is established considering the control point resource - the Bore Grind. In effect, the MPS concurrently schedules Final Assembly and Bore Grind, both maximizing Bore Grind capacity and fully using it.

Since the two week supply of finished goods requested by corporate marketing had been depleted, the Bore Grind was scheduled at maximum output (six days plus a voluntary seventh). There was no set-up time, thus sequence and lot size were unimportant. Output was master scheduled accordingly.

The inventory buffer is used to prevent starvation of the control point resource thereby protecting the schedule and throughput. The actual composition of the buffer is determined by the control point MPS. The timing of the release of materials into the shop is based on the expected lead-time from the gateway operation to the buffer.

In the bearings plant, normal lead-time from screw machine to bore grind was four days. As a starting point, materials were to be released four days prior to their planned arrival at the bore grind inventory buffer. The actual quantity of inventory to be stored in the buffer was initially set at one day's supply but was quickly reduced to one shift's supply.

As regards the release of materials into the shop, this is based on the requirements of bore grind. Here a simple input/output control was established whereby the gateway screw machine department produced the quantity that the Bore Grind had produced the previous shift. Material was provided to the gateway in the desired sequence and at an offset timing dictated by the MPS, but release was carefully controlled by the input/output control. Material then flowed reliably to the control point on a first-come-first-serve basis unhampered by capacity constraints.

Company B

The plant manufactures a wide variety of wooden furniture. The manufacturing process is constituted by four phases: rough mill, machining, assembly, finishing, and shipping.

Rough lumber is purchased from vendors and converted into blanks and panels with rough dimensions at the rough mill. In the machine department, all the furniture parts are then machined into finished dimensions and prepared for shipment to other companies or transferred to assembly. All end items are then final assembly and either painted or treated with a natural finish in the finishing room, and then, finally shipped to the customers. Each furniture part requires a unique machining operation sequence which can involve up to seven woodworking machines out of the 16 machines in the Machining Department. The Assembly Department consists of three assembly lines. Assembly line #1 was identified as the capacity constraint resource (CCR) in the assembly room. Machine #3 is the CCR in the machine department. Machine #14 is also heavily loaded and is treated as a constraint.

To maximize utilization of the assembly CCR, the parts for line #1 are to be first processed at the machine room in order to start the subassembly process on line #1 as early as possible. The subassembly schedule of the frame and end panel for the dresser can be determined by back scheduling so that they are completed by the completion time of the dresser drawers on line #1. Analogously, the Machine Department CCRs (machine #3 and #14) are loaded as early as possible and forward scheduled so that idle time is minimized. Various buffers have been established. The function of these buffers is to absorb any fluctuation occurring in operations that precede the CCR. The size of the total time buffer has been approximately fixed to one-half of the firm's manufacturing lead time.

A detailed schedule and strict management control of the process is needed only at the schedule release points. Since all other points in the process require little control, the sequencing rule after release is a simple a first come first served priority. All the scheduled release points are derived from the CCR's schedule by subtracting the constraint buffer from the CCR's schedule.

Company C

The Company is a textile mill that produces fabrics for a variety of end uses such as upholstery and drapery products. The production process at the textile mill is quite simple. At each step in the manufacturing process, the material can be transformed into many distinct products. A given item from yarn prep can be dyed many different colours. Similarly, yarn of a specific colour from the dyeing stage can be woven into many different patterns at the looms. The number of end items is very large (thousands of distinct items); each end item competes for the use of the same resources since the routings are the same.

The plant is characterized by expensive machinery and long set-up times. The set-up time may vary greatly from one resource to the next and the required set-up time at a given resource may vary from one set-up to the next, depending on the nature of the change. Thus, the natural tendency is to process material in large batches. The planning lead times used (12 weeks) for the various stages of production, clearly show the long lead times allowed for proper production sequencing.

To satisfy the off-the-shelf demands of the marketplace, a stock buffer was appropriate for the finished goods area. However, after applying the Theory of Constraints philosophy and a drum-buffer-rope system to the process, the production lead-time is reduced from 12 weeks to less than 4 weeks. Therefore, the finished goods inventory stock buffers was reduced to four weeks. In addition, to protect the plant from vendor delivery problems, raw yarn was planned to be stocked in the plant. A one-week stock buffer of raw material was deemed to be more than adequate.

Having set up the stock buffers, the raw material flow objectives were realized by effectively implementing a DBR system of material control. The looms were identified and confirmed as the capacity constraint resource (CCR) for the process. Rules for converting the customer demand and forecast (now restricted to a 4-week period) were developed. Essentially this consisted of setting up batch sizes (warp lengths) and sequencing rules. The batch sizes were reduced by an average of about 30 per cent and sequencing rules were established that balanced due-date priorities and set-ups at the looms. By taking advantage of the shorter changeovers afforded by some set-ups, these sequencing rules enabled the planners to introduce only minimal distortion to the due-date priorities without losing capacity at the CCR. It is important to note that the objective of the sequencing rules is not to balance inventories against set-up costs, but rather to balance customer priority and capacity at the CCR.

Establishing the location of the time buffers was a relatively straightforward exercise. The fact that weaving was the only CCR in the plant meant that there would be two time buffer locations. One time buffer was placed before the looms (weaving operation), and the other time buffer was established at the finished goods level. It was agreed that a 3-day buffer at both the looms and finished goods was a good starting point.

It was decided that the release of material into the system would be based on the various lead times. However, every step in the process is a divergence point. That makes every step a schedule release point also. Thus, detailed schedules had to be released to each work centre.

Company D

The plant produces data centre cooling solutions. The product is assembled-to-order from components and subassemblies to meet the design specification. There are five general product models, although over thousands unique designs are available according to management. The factory is arranged along an assembly line, which is divided into 40 operations. Sixty per cent of components are purchased; the others are produced internally using production cells which operate as separate unit. There are a relatively small numbers of components, about 3000 part numbers that are used to produce a relatively large number of end items.

The production planning and control system used is a combination of JIT, TOC and MRP. The MRP system is used for master production scheduling, for rough-cut capacity planning, for material requirements planning calculations. No shop floor control module is implemented. MRP data is used to provide customer promise dates and to support product-costing calculation that are used for external financial reporting.

The kanban method of material movement of subassemblies to the final assembly line is used. Suppliers also use a triggering system to replenish purchased components. The plant has implemented a Theory of Constraints approach to production planning and control. The shop floor is controlled by the use of the drum-buffer-rope and buffer management techniques.

Four base models are used to develop the sales forecast and the master production schedule. Options and attachments are forecasted as a percentage and the quantities placed in the master production schedule. The MPS then is fed into the MRP module for the material requirements calculations.

The factory tries to maintain the first two weeks in the MPS as a frozen time period where new orders are not placed. The assembly line is scheduled for a 20 units per week build rate. The factory uses a one-week shipping buffer, which is supported by the master production scheduling dates used by the master scheduler to launch units as the gating operation. A two-day buffer is planned at the constraint in the assembly line. Actual manufacturing assembly time is two to three days. Therefore, MPS executes the drum-buffer-rope method. The drum is set at the constraint in the assembly line. The transmission of the build packets that establish the build sequences is the rope. Finally, a two-day buffer exists at the constraints. An overall five-day shipping buffer exists as part of the MPS calculation.

Priority planning for purchased parts is largely controlled by the MRP system. A sales order has five days shipping buffer created in the offset from the ship date to the build date.

Priorities planning for manufactured components are managed using the drum-buffer-rope technique. A buffer is planned at the assembly line constraint, which is the Freon charging and vacuum task. A space buffer exists after the constraint as well. The constraint buffer is one day. Material flows into the assembly line from the feeder operations in accordance with the build packet. The constraint buffer also establishes a minimum and maximum level of the major component.

As regards priority control, each cell assigns one employee to be a team representative on a rotating basis for four months. There is no use made of a daily dispatch list or a manufactured shortage report. If there is a problem at the constraint buffer, the team managers may also become involved in creating the action plan, as might the Purchasing Manager if purchased part shortages are involved.

Company E

The factory produces approximately 200 end items and production focus on the manufacture of suites of furniture rather than on individual pieces. A suite typically consists of about seven items for a dining room and five items for a bedroom. There are approximately 160,000 part numbers including sub-assemblies and components. The typical bill of material is five levels deep. About 95 per cent of the furniture produced is made to stock with deliveries made from the finished warehouse stock.

Manufacturing lead-time is 25 days. It is estimated that about 75 per cent of all manufactured components require less than seven days lead time with the longer time being required for components that have machining operations performed by outside contractors. The factory uses the manufacturing lead-time for purchasing requirements and for material release. Actual manufacturing lead-time is the results of buffer management. Currently there is a four-day buffer established for manufactured components and an additional five days allowed for release of raw material into the gating operation.

The plant operates with a material requirements planning system, which is used for master production scheduling, capacity requirements planning, material requirements planning calculations, shop floor scheduling, and purchasing. In the 1990, the company adopted the Theory of Constraints philosophy. Primary use is made of the drum-buffer-rope technique. Currently, the MRP system is used for master production scheduling and for purchase parts scheduling. The plant is organised along the factory-within-a-factory concept, and there is an active program to reduce set-ups and run sizes throughout the plant. There is no use made of the kanban method, homogenous master production scheduling, or levelled master schedules.

The order policy used in the MRP planning functions is lot-for-lot with a minimum order quantity of 150 units. Manufacturing lead-time in the MRP system is 25 workdays. Total quoted customer lead-time is 45 workdays, which includes the 25 days plus 20 days for distribution and administration. The lead-time is used only for purchasing information.

The 45 days used in the MPS as a frozen time period permit cuttings to be made at the gating operation from dried lumber in sufficient quantities to build the desired amount of furniture. Once approved, the MPS is loaded into the MRP system to generate purchasing requirements. A final assembly schedule (FAS) is prepared for the end item. The FAS is the drum used to establish the pace of production for the plant. Management believes that the marketplace is the current constraints to the system so the final assembly lines are used to establish the internal constraints by adjusting workforce assignments. In this way, the FAS is kept equal to the MPS. Production is monitored on a daily basis and adjustment to capacity are made using overtime to keep the assembly lines on schedule.

Part priorities are established by two general approaches. For purchased components, MRP logic is used allowing 45 days lead time for all parts. The MPS identify the due date for the assembly of the end item in weekly time periods. The production requirements for end item explode and time phase via the MRP calculation and purchase orders are issued. Part priorities for manufactured parts are scheduled according to a four-day buffer established prior to the assembly lines, at the drum. Material is released into the gating operations according to the FAS date adjusted for lead-time. The lead-time is calculated for each manufactured component going into the final assembly. The lead-time is calculated by adding the longest operation time in the part's routing for processing the entire batch and adding four hours for every other operation or the actual processing time if it is greater than four hours. This calculation determines the start dates for all components for the final assembly. The due dates are communicated to the shop on a buffer schedule report. Since the drum has been established at the assembly line, all manufactured components are scheduled across the constraint. As a result, all manufactured parts are identified on the buffer schedule.

Priority control focuses at the buffer prior to the assembly lines. There is no daily dispatch list used at the plant nor is a shortage list prepared. The buffer due dates are determined for components that feed the constrains (the assembly line) and are communicated back into the shop by the buffer schedule. The changes in the buffer status are determined each day and adjustment are made in the buffer status report. The buffer report schedule is the source for expediting parts as the need arises in the production process.

Production Control in a TOC Environment: Evidences from the Cross-Case Analysis and an Interpretative Framework

This section describes the results of the cross-case analysis to highlight how production control is carried out under a TOC approach. The ultimate goal is to point out the main features of this production management method. The paragraph is organized in two sections: the first provides a pithy overview of the method; the second describes, in more detail, the key distinguishing characteristics of TOC regarding production control. The analysis is carried out through a comparison of TOC with three other shop floor control systems.

TOC at glance

All the case studies clearly highlight that only a few work centres within the factory control the output of the entire factory for each product line. Managing these capacity constraining resources (CCRs) or bottlenecks optimizes the global output of the factory. This is done by the so-called DBR methodology, which synchronises resources and material utilisation in the factory (see case C, D and E).

The *Drum* is the system schedule or the pace at which the constraint works. In order to deal with achievable production plans, finite schedules for only the CCR operations are developed. Therefore, these control point schedules are set so as to exploit the internal constraints while satisfying customer demand. At the control points, the schedules are offset by the expected lead-time (the sum of lead times of all phases needed to pass from the control point to the end item). Since the control point usually represents the work centre with the least capacity, all work centres between the control point and the final assembly need to have excess capacity, thus minimizing delays and permitting reliable lead-times.

After having developing achievable plans, Rope provides orders release and material control movement by means of communications between critical control points to ensure synchronisation. Production in non-bottleneck work centres is triggered by the "rope" at the bottleneck that signals the release of raw materials from the beginning of production process. More in detail, we could say that the definition of production plans requires the concurrent development of a series of specific schedules for CCR identified in the production process. However, the other operations carried out at no-bottlenecks centres have to be correctly linked to the control points. As highlighted in case studies' descriptions (section 5), most of the firms "reduced" the MRP procedure to a simple calculation of requirements for raw materials or for components to be purchased; as a consequence, usually, only purchasing orders, not production orders, are issued (see case E). Therefore, the components of intermediate levels of the bill of materials are not managed at the warehouse level and calculation of net requirements for them is not used. In this perspective, the gating operation(s) releases material in accordance with the finite schedule at the bottleneck and materials flow through the shop as required to support the bottleneck buffer. Thus, a first-come-first-serve priority often ensures that no orders are delayed. The input of materials into the shop based on usage by the control point assures that work in process inventories and lead times are controlled. In this manner, raw materials are pulled into the shop, not pushed. After being released, materials are processed in a first-come-first-served priority and are pushed between all operations. Consequently, in a TOC environment the material movement control system can be described as a combination push/pull system. More specifically, the downstream operations are finite forward loaded based upon the capacity of the CCR resource. The upstream operations are back scheduled from the CCR using MRP logic (see case B).

As regards the physical movement of material with TOC, the transfer batch is optimized to maximize throughput, not automatically set to the process batch size, as is normally done. The process batch itself is variable, a function of the schedule, potentially varying by operation and over time. Both lot sizes vary, with the goal of maximizing production across the CCR. However, rather than splitting the orders on the CCR, as is normally done, the orders are split on the non-CCR machines, where more setups are done. Larger lot sizes are created on the CCR machines and smaller lot sizes on non-CCR machines. The transfer batches are usually smaller than the process batches (see case B).

The third component of the DBR methodology is *Buffer*. Buffers are strategically placed inventory to protect the system's output from the variations that occur in the system. In TOC, it is critical to protect the schedule at the CCR and thus ensure that the control point is never starved. Hence, a first time buffer is established in front of the CCRs and any critical operations that feed the CCR. This is to protect the CCR from statistical fluctuations that would stop this critical process (see case B and C). As seen in the description of the case studies, a second buffer should be placed in the shipping area. This is an offset from the promised ship date to the due date from the final assembly. The size of the shipping buffer depends on the variability that must be dampened (see case D).

A third buffer that should be created is an assembly buffer (see case D and E). Assembly buffers are time buffers created to ensure delivery of purchased components do not interrupt the final assembly schedule. A second use of the assembly buffer is to protect the assembly line from the same type of variability within the factory.

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Distinguishing characteristics of TOC regarding production control: an interpretative framework

In order to better understand the TOC approach, its main characteristics are examined in detail in the following. The analysis is carried out comparing TOC with the three most relevant shop floor systems, namely Dispatching, Kanban and Daily Rate, each of which is hereinafter briefly described.

Merging the empirical evidence summarized in the previous section, with the characteristics of Dispatching, Kanban and Daily Rate systems as widely describe in the literature, the key elements characterizing TOC approach are found out (Table 1).

Dispatching is a well-known as a traditional production control method used in manufacturing systems characterized by generic production processes and able to generate a wide range of parts such as job-shops. Parts are produced in lots and the product bill of materials is generally multilevel. After the formulation of the production plans, the MRP procedure generates (using an infinite capacity algorithm) both job orders (work orders) and purchasing orders. As regards work orders, MRP issues daily dispatch reports to the manufacturing, which define the jobs that are present in each area and when each job should be completed or issued. According to a push logic, these dispatch lists specify which jobs should be completed (and when they should be completed) in order to ship manufactured goods on schedule. Lots move on operation completion and the production batch is equal to the transfer batch. As each required operations defined by the MRP dispatch reports is finished, personnel completing the action make entries into the MRP system. These entries inform the system about the status of all orders and allow a detailed control of material movement [38].

Kanban is well known as the celebrated scheduling system related to just-in-time (JIT) production developed at Toyota Motor Corporation to minimize inventory. Kanban uses the rate of demand to control the rate of production, passing demand from the end customer up through the chain of customer-store processes. Therefore, the

Shop Floor Control Characteristics	Dispatching	Kanban	Daily rate	Toc/Opt
Shop Floor Control Goal	Maximize efficiency	Minimize inventory	Ensure a regular production flow	Optimize bottleneck operations
Capacity evaluation	Infinite capacity requirements planning	Finite capacity requirements planning through Kanban cards	Finite capacity requirements planning of the whole line	• Finite capacity requirements planning for bottleneck operations • Infinite capacity requirements planning for non- bottleneck operations
Order release	Triggered by MRP schedules from the first stage	On the basis of downstream consumption	On the basis of production programmes (Daily Rate)	Production in non-bottleneck work centres is triggered by a "rope" at the bottleneck that signals the release of raw materials from the beginning of production process
Priority assignment	• Dispatch List (Priority Rules) • PUSH Scheduling	• Rack with Kanban production cards • PULL Scheduling	• First In - First Out • PUSH Scheduling	• Bottleneck work centres: Dispatch List with priority rules • Non-bottleneck work centres: First In - First Out or on the basis of downstream consumption • PUSH/PULL Scheduling
Work in progress	Queues of materials upstream of the work centres	In standard containers upstream and downstream of the work centres	In areas or deduction points along the line	Materials are placed: - in front of bottleneck work centres - at the intersection of non-bottleneck paths and the path from a bottleneck to its orders. The are no or very little buffer inventory for non-bottleneck work centres
Production and transfer batches	• Lot movement on operation completion • Production batch = transfer batch	• Movement of standard containers on request of downstream centres by means of Kanban movement cards • The transfer batches are usually smaller than the process batches	Piece movement in a continuous flow	• Lot movement on operation completion • Production batch ≠ transfer batch • Large lots for bottleneck operations and small lots for non-bottleneck operations
Buffer type	Part buffer	Part buffer (Kanban containers)	• No buffer in rigid transfer lines • Part buffer in free-transfer lines	Time buffer
Buffer Size	Function of checks and balances system of MRP and physical storage capacity area	Based on size and number of Kanban cards	In free-transfer lines buffer size determined by physical storage capacity area	Number and value of parts vary while processing time is held constant
Work load control	• Variable WIP level • Workload is not controlled	• Almost constant WIP level • Workload controlled by Kanban cards	• Constant WIP level • Workload controlled by daily rate	• Constant WIP level • Workload controlled through the ROPE system
Issue and registration of materials	Picking list with simultaneous registration	Kanban cards from first centres with simultaneous registration	• Material issue on the basis of the daily rate schedule • Ex-post registration in backflush	Picking list with simultaneous registration
Data collection/monitoring	All work centres	All work centres	• Milestone work centres	Bottleneck work centres

Table 1: Distinguishing characteristics of the four shop floor control systems: an interpretative framework.

supply or production is determined according to the actual demand of the customers. In detail, the production system is driven by a master production schedule released only to final assembly centres of the production process. No production orders are generated by the MRP procedure, which is used solely for the computation of purchasing requirements. Kanban control contains only local information flows. The cards (kanbans) circulate between a buffer and the immediate upstream machine. When a downstream machine picks up materials to perform an operation, it also detaches the card attached to the material. The card is then circulated back upstream to signal the next upstream machine do another operation (pull logic). Small inventories of semi-finished products are maintained at each work centre of the production process in standardized containers that are moved following strict rules of use. The number of kanban cards limits the flow of products so as kanban cards serve to ultimately control work-in-progress (WIP) and eliminate overproduction [39].

Daily Rate is a repetitive planning control method typical of manufacturing systems characterized by very high level of production repetitiveness and stability [40,41]. In these situations, management is characterised by an overall vision of the production system, which leads to focusing on the entire process. Within this scenario, the fundamental objective of the shop floor control sub-system is to control the uninterrupted flow of materials that move through the machining centres according to a continuous flow, not in predefined lots. The high production volumes and low throughput times mean that the traditional control system typical of job-shops - the work order - is difficult to use in these situations: the focus of control is on resources rather than orders. Formulation of the production mix to be carried out, by day and by line, defines the so-called Production Daily Rate that is the true regulator of these repetitive manufacturing systems. This daily production programmes, which are defined taking into consideration the actual capacity of the lines, regulate the order release and materials movement given that the classic MRP procedure is reduced to a mere calculation of requirements with no formulation of production orders. Materials are issued to the plant according to the daily rate and move along the plant according to a first in – first out logic. Between the various stages, there are no decoupling stocks. *Data collection and monitoring* are carried out only in the most critical stages or milestone operations. If repetitive manufacturing is characterised by even more favourable operating conditions (product simplicity and reduced range) it is possible to have an even simpler data collection system, which only records the order opening and closing: auto-open/auto-close. Consumption of raw materials and components can be deduced from the output volume through the bill of materials. This technique allows ex-post construction of issues based on finished part receipts and it is known by the term backflushing or post-deducting.

A synthetic description of the different characteristics of the four shop floor control systems previously looked at (i.e. Dispatching, Kanban, Daily Rate and TOC) is shown in table 1.

Conclusions

Using an empirical approach the paper describes how production control is carried out under the TOC approach. The analysis of empirical data highlights the key features of TOC approach and an interpretative framework has been proposed to compare TOC and other well-known shop floor control systems, namely Dispatching, Kanban and Daily Rate. Eleven characteristics have been chosen for doing this comparison (see left column of Table 1).

The results clear highlight the differences among these systems and suggest that the importance and timing of each activity and how they are carried out are determined by the manufacturing process, its production characteristics, practices and requirements.

For example, in manufacturing systems characterized by high level of variability of both product structure and process composition (such as the Dispatching and TOC), SFC sub-system must know in detail data such as the order number, order quantity, bill of materials, machining routings etc. In this context, the amount of detailed information required is enormous; consequently, the type of information and level of detail required by the SFC sub-system is high.

This kind of information is not required in highly repetitive production system: the planning system (the front-end level) specifies common routings and standard bill of material. The SFC sub-system in this case emphasizes execution and does very little planning.

This influences the degree of indeterminateness of the context within which SFC activities are developed. The degree of indeterminateness could be expressed as the number of unexpected events to be faced during the executive stage. This number is very high in medium-low repetitive production given the vast range of manufacturable parts and the consequent routing complexity. Conversely, in highly repetitive systems, the variability of routings does not allow much variation from what was established at the planning stage. Therefore, the amount of uncertainty is much less in SFC.

Another aspect worthy of note is about the level of autonomy of foremen during the control of production schedules. In highly repetitive production, once the production programmes have been determined and the daily production rate has been defined during planning, the task of personnel involved in SFC is only to guarantee maintenance of the production flow. Decision-making latitude is reduced. The state is obviously very different in systems with very low levels of production repetitiveness and stability. Here, SFC sub-system has a large amount of decision-making latitude due to the uncertainty about the jobs and the high level of detailed information.

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